A Review of Applicable Materials for 3D Printing a Biomechanically Accurate Cervical Spine Model for Surgical Education & Case Preparation

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INTRODUCTION

- Given their high costs and a multitude of limitations, cadavers remain a less-than-ideal means of surgical planning and case rehearsal
- One alternative to cadaveric material is the use of Finite Element Analysis (FEA) models; advanced computational techniques to predict or test the mechanical properties of a structure, but do not allow for hands-on teaching, planning, or testing.
- **To avoid the drawbacks from cadavers and Finite Element Analysis studies (FEA), 3D printing can be used.**
- This review intends to identify key biomechanical properties of the human cervical spine and compare them to 3D printing materials currently available to guide the development of a high fidelity 3D printed human cervical spine model that can be used to advance spine care (Figure 1).
  - As Fused Deposition Modeling (FDM) 3D printers are the most affordable and currently have the largest variety of materials that it can use, we focus on comparing applicable materials for FDM printers to the cervical spine.

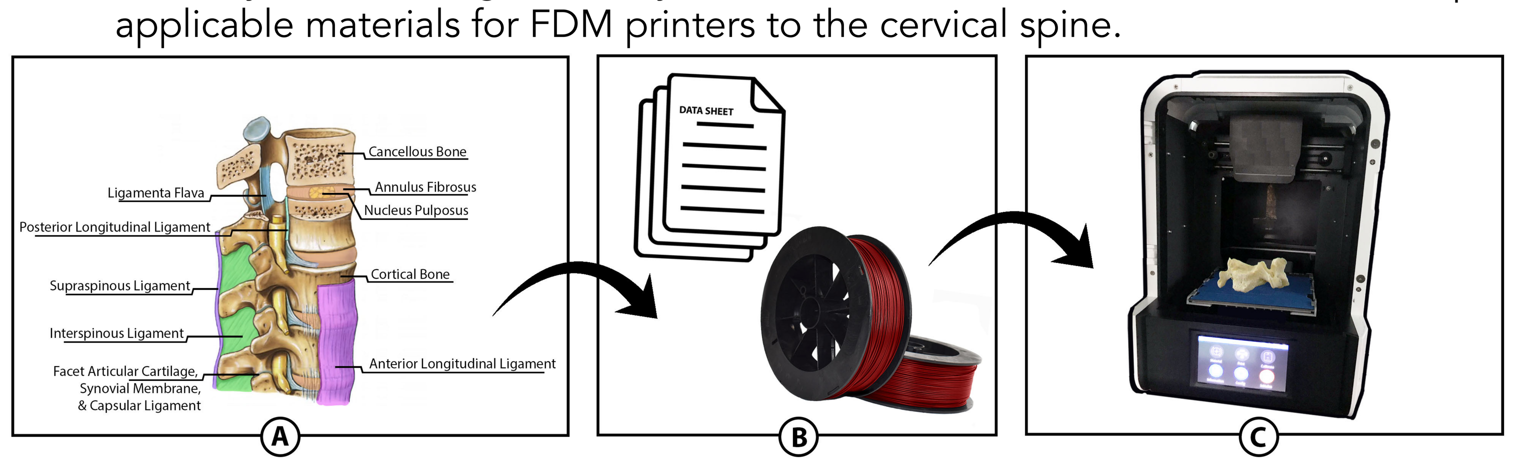

Figure 1: The overall process for 3D printing a biomechanically accurate spine model for educational purposes involves *A)* compiling numerical data from across the literature in regards to Young's Modulus and Poisson's ratio for key anatomical constructs, *B)* reviewing data sheets of 3D printing materials currently on the market to determine which represent the values from *A* most appropriately, and *C)* modeling the anatomical components via software, printing the components with the chosen materials from *B* with an FDM 3D printer, and finally, assembly of the structures. Biomechanical validation testing can be completed on the printed model prior to use for surgical education and training.

METHOD

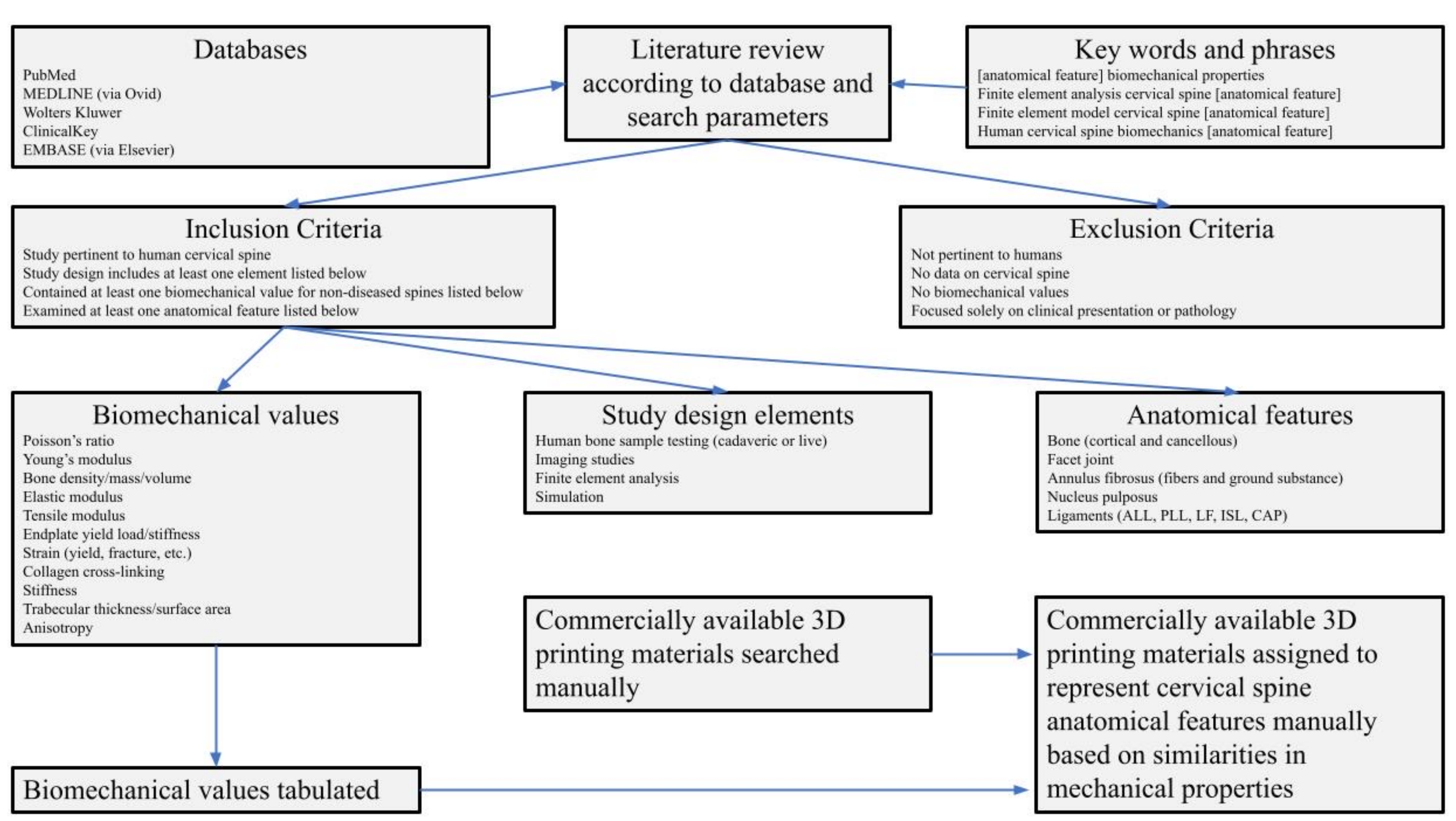

Figure 2: Flowchart representing data collection and assignment for cervical spine model 3D printing. A flowchart illustrating the process of the literature review and incorporation of data for 3D printing a human cervical spine model. Databases consulted and search parameters were listed. General descriptions of inclusion and exclusion criteria were outlined, as were specific biomechanical values, study design elements, and anatomical features that were pertinent to the review. Biomechanical values of the spine, and mechanical values of the 3D printing materials were compiled and compared to one another. 3D printing materials were assigned to represent specific cervical spine anatomical features according to overlap in biomechanical and mechanical values.

RESULTS & DISCUSSION

Table 1. *Summary table* – Referenced literature range of Young's Modulus and Poisson's Ratio for the anatomical components described, accompanied by suggested FDM material for printing

Anatomical Focus	Young's Modulus	Poisson's Ratio	Suggested FDM Material
Cortical Bone	10,000 - 12,000 MPa [3–10]	0.29 - 0.30 [3–10]	CF-Nylon, CF-PLA
Cancellous Bone	100 MPa - 450 MPa [3–10]	0.20 - 0.29 [3–10]	Armadillo™
Facet Articular Cartilage	10 MPa - 11 MPa [3,9,12–20]	0.30 - 0.40 [3,9,12–20]	NinjaFlex®
Facet Synovial Membrane	12 MPa [3]	-	NinjaFlex®
Annulus Ground Substance	2.5 MPa - 4.7 MPa [3–6,8,9]	0.25 - 0.45 [3–6,8,9]	TPE
Annulus Fibers	110 MPa - 500 MPa [3–6,8,9]	0. 30 - 0.45 [3–6,8,9]	Armadillo™
Nucleus Pulposus	1 MPa - 3.4 MPa [7,10,19]	0.49 [7,10,19]	TPE
Anterior Longitudinal Ligament	10 MPa - 30 MPa [4,5,8,17]	0.3 [6,8,17]	Stratasys FDM TPU 92A
Posterior Longitudinal Ligament	10 MPa - 20 MPa [4,5,8,17]	0.3 [6,8,17]	Stratasys FDM TPU 92A, NinjaFlex®
Ligamenta Flava	1.5 MPa - 50 MPa [4,5,8,17]	0.3 [6,8,17]	Cheetah™
Interspinous Ligament	1.5 MPa - 10 MPa [4,5,8,17]	0.3 [6,8,17]	MatterHackers PRO Series TPU
Capsular Ligament	10 MPa - 30 MPa [4,5,8,17]	0.3 [6,8,17]	Stratasys FDM TPU 92A

All values of Young's modulus of the FDM materials presented here have been determined in accordance with ASTM D638 or equivalent testing standards.

- While FDM technologies are comparatively affordable, their main drawback is that the prints are notably anisotropic
  - This not only impacts the biomechanical properties of the printed components but also their longevity when subject to repeated use.
  - In attempts to mitigate the effects of anisotropy, some software now allows for specific sections of the model to be designated with certain infills of one's choosing.
    - There now exists the possibility for load-dependent infill placement as well, which would be especially useful for printing cortical and cancellous bone of varying porosities, the facet joints, as well as regions of the intervertebral discs.
    - Designers can choose an infill pattern and infill percentage prior to printing, which can be leveraged to develop models of variable strength (subsequently, Yo

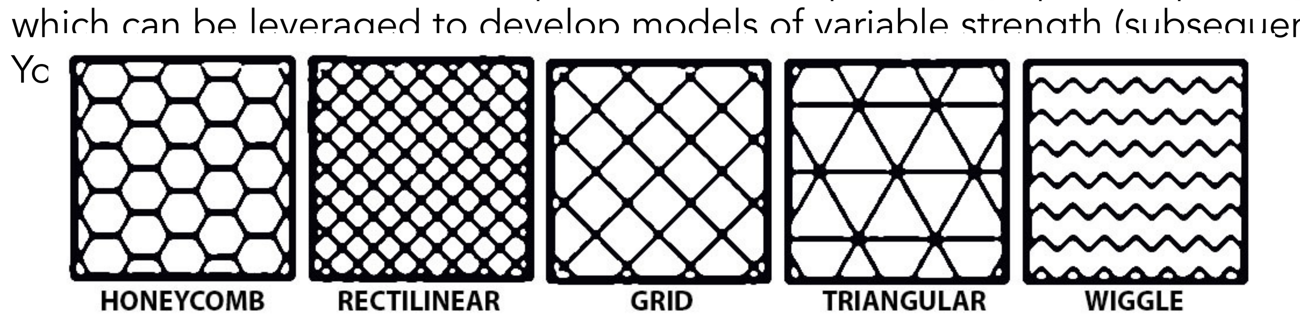

Figure 3: Standard infill patterns. Honeycomb yields the strongest print, while comparatively weaker prints contain a wiggle infill.

  - Infill percentages: a higher value results in stronger prints; yet they are heavier and more costly since more material is used when printing.
  - The strength of a print can be further enhanced by increasing extrusion width, shell thickness, layer heights, layer adhesion, or by using materials reinforced with glass or carbon fibers.
- More representative materials may be available for other denominations of 3D printers, such as the J750 from Stratasys, which allow for customized blending of materials

CONCLUSION

- Given the deficiencies associated with cadaver-based training in surgical education, 3D printing has been recognized across disciplines and institutions as a promising alternative
- Advancements in 3D modeling and printing technology allows surgeons to create cost-effective anatomically correct models with or without pathology that can be useful for teaching, planning, and testing purposes
  1. Using readily available advanced imaging techniques, surgeons can use 3D modeling to create an accurate computational representation of patient anatomy
  2. Surgeons can use 3D printing materials with biomechanical properties similar to that of healthy or pathologic human anatomy to create accurate physical models.
  - **Combining high resolution imaging and 3D printing techniques, surgeons can create highly accurate representations of real human anatomy.**
    - These models can be used by surgeons to teach surgical residents about the anatomy of an operative region, to practice surgical procedures prior to performing them on patients, or to be used in a wide variety of biomedical testing applications such as testing of pedicle screw application *in vitro*.
    - 3D printing pursuits of spinal structures can be improved by suggesting materials that are more representative of their biomechanical properties

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